The Development of New Actuation Systems for Mechatronic Toys

by

Michael T. Jensen

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ABSTRACT

The actuation systems currently used in low-cost mechatronic toys have numerous areas for potential improvement. The development of a new actuation system that is more efficient, produces a more realistic product, or is cheaper has the potential to significantly increase both the quality of the final product and its market viability. Research into potential ways to improve these systems has resulted in three new potential technologies, flexible shafts, output switching, and voice coil actuators using flexural transmission. Each of these products is still in the initial stages of development, but each also has the potential to significantly increase the realism of current and future toys. The most developed of these ideas is use of voice coils with flexural transmissions. This system has the potential to generate significant torque outputs without large, multi-stage transmissions, potentially resulting in significant reductions in unwanted mechanical noise.

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Acknowledgments

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1.0 Introduction

This project was initiated by the Hasbro corporation in order to research new actuation systems for current and future mechatronic toys. The goals of these new actuation systems are to produce a more lifelike experience from the toy, to improve the efficiency of the actuation system, and to reduce the cost of production. In order to understand the problems with existing actuation systems, and to find potential areas for improvement, numerous toys were disassembled and examined. The results of these examinations indicated several areas for improvement upon existing designs.

One of the largest areas for improvement is in increasing the realism of existing toys. Many of the current toys examined use only one actuator to produce all of their outputs. Driving all of the outputs from a single actuator requires a significant quantity of gears, cams, and linkages which all produce mechanical noise which detracts from the toy's believability. In addition, this type of system does not provide for independent outputs. In some of the toys the appearance of independence is generated using cams with dwell periods, but this method significantly limits the range of possible outputs.

In looking to improve upon the existing actuation systems, a number of different ideas were examined. These ideas included actuation with systems including shape memory alloys, bi-metallic strips, pneumatic and hydraulic systems, air bladders, chemical reactions, compliant materials, static electric interactions, and voice coils. These potential actuation systems ranged from easily plausible to significantly impractical, but provided a solid starting place for the development process. From this broad pool of ideas, three concepts were chosen to receive significant focus. These ideas were the use of flexible shafts, output shifting, and the use of voice coil actuators with flexural transmissions. Each of these systems offers potential increases in the believability of the toy by either reducing mechanical noise, providing truly independent outputs, or both. Initial proof of concept models for both the flexible shaft drive system and also voice coil actuation using a flexure transmission have shown that implementation of the system is possible, and that these systems have the potential to offer significant benefits, however, in both cases, there is still a significant amount of work to be completed before these actuation systems can be commercially deployed.

2.0 Examination of Existing Actuation Systems

In order to gain a better understanding of the design requirements for new actuation systems, and to gain a better understanding of the areas where there are significant opportunities for improvement a variety of mechatronic toys of varying size, cost and complexity were disassembled. The information from these toys provided numerous insights into the toy design process, and provided first hand experience with the problems which the new actuation systems would attempt to solve. A sample of this process is provided in the account of the disassembly of both a Baby Furby and a FurReal line Newborn Cub[1]. These toys were part of the initial series of disassembled toys and provide a representative sample of the different actuation systems found in the majority of the toys.

2.1 The Furby ™ Line of Toys

One of the product areas in which Hasbro is looking to make improvements is the Furby line of toys. In these toys the mechatronic function are designed to provide a series of basic responses to user input and interaction. These responses include movement of the eyelids, mouth, limbs, and body. Various combinations of these movements are accompanied by audio responses to simulate higher level interactivity. In the initial, user style, testing of the toy the largest area for improvement appeared to be in the sound made by the actuation system. While in many cases the mechanical sounds were partially covered by the audio responses of the toy, mechanical sounds were present which detracted from the believability of the toy. The disassembly of the Baby Furby, which is shown in figure 1, is particular interest due to its high internal density and also the more sophisticated interactions that it attempts to represent.

2.1.1 Examination of the Baby Furby

The Baby Furby exhibited three main outputs during the initial user style testing. These

1 The Baby Furby and Newborn Cub can be found on the Hasbro website at the following two addresses respectively:
http://www.hasbrotoyshop.com/ProductsByBrand.htm?BR=569&ST=SO&ID=17244&PG=1
http://www.hasbrotoyshop.com/ProductsByBrand.htm?BR=688&ST=SO&ID=17389&PG=2

outputs were movement of the mouth, movement of eyelids, and movement of the body relative to the legs to give the impression of leaning forward and backward.

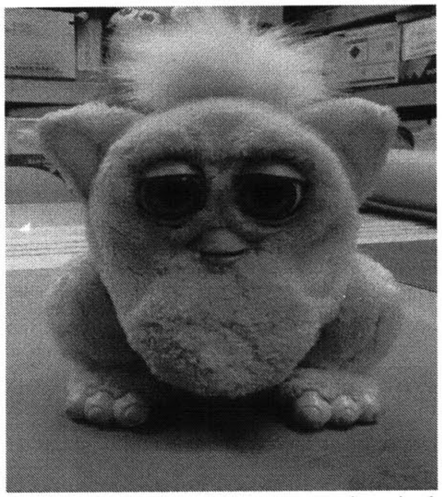

Figure 1: A front view of the Baby Furby. The output actions include the movement of the eyelids, the mouth, and the body relative to the legs

These outputs appear to be independent, but actually all dependent motions driven by one rotational motor. The output routines of the toy are triggered by sensors on its chest and within its mouth. Once the behavior of the toy had been thoroughly observed and recorded the outer, fur like covering of the toy was removed revealing the first details of the underlying systems, as is shown in figure 2.

Figure 2: The Baby Furby with the outer covering removed. The cords of the chest sensor are visible in the front, and some of the internal actuation is visible through gaps in the plastic housing.

At this point the chest sensor is visible as is the majority of the eyelids and the compliant surface of the mouth. The plastic linkages that connect the eyelids to the actuation system are also visible at this point. Removal of the legs revealed the inclusion of a spring-loaded clutch, shown in figure 3. This mechanism decouples the legs from the internal actuation system if sufficient torque is applied to the legs. This system protects the integral systems from damage if the user attempts to prevent the motion of the toy, or to back drive the system. The clutch is also designed to provide only one position relative to the drive assembly in which it is engaged so that the position of the legs is known when they are coupled to the actuation system.

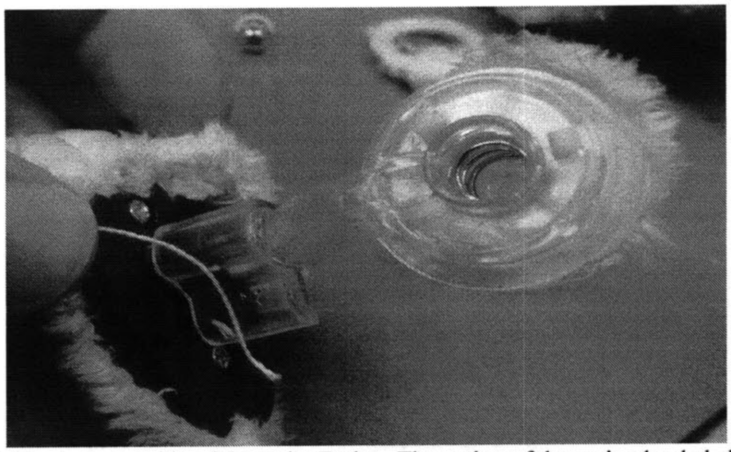

Figure 3: The leg assembly of the Baby Furby. The spring of the spring loaded clutch is visible. This spring keeps a notch on the outer ring aligned with a matching ridge on the internal dive mechanism unless potentially damaging torques are applied.

Further disassembly of the Baby Furby revealed the internal components of the actuation system. The first element observed was the density of the internal components. Virtually the entire integral volume is filled, as can be seen in figure 4, and it is clear that careful attention was given to designing the components to fit into compact assemblies. The main elements of actuation system consist of a single rotary motor, plastic spur and worm gears, and a series of closed cams shown in figure 5. The use of dwell periods in the cams allows the one actuator to appear to provide three independent outputs. The motion of the body of the Baby Furby relative to its legs is driven by a cam attached to a one-axis slide. This slide produces the rotation of the body relative to the legs with the help of a set of fixed gears which force the rotation. The position of the body relative to the legs is sensed by a a series of rotary switches which can be seen it the center of the main shaft shown in figure 4.

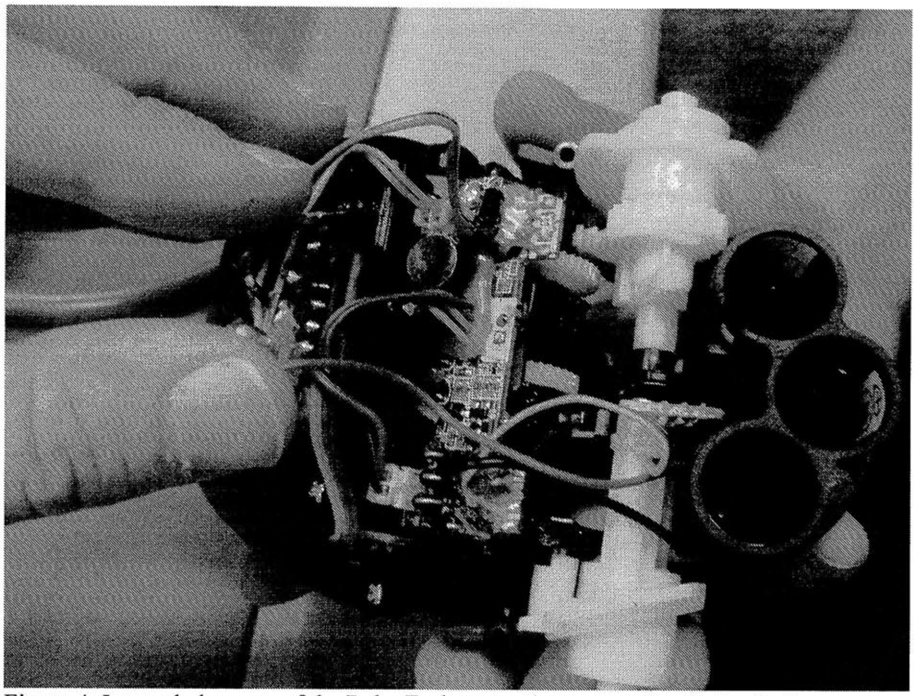

Figure 4: Internal elements of the Baby Furby actuation system for the leg/body movement after removal of the back panel. The white plastic in the center left of the picture is the drive shaft for the movement of the body relative to the legs. In the center of this shaft is a very simple rotational sensor composed of several radial switches to give rough position information. The movement of the body is driven by the single motor behind the main circuit board.

When the main circuit board is removed it is possible to see the main transmission segment of the actuation system as well as the cams that drive the outputs. The motor output is run through two worm gear assemblies in series to dramatically increase the torque output and is then delivered to the main cam shaft. The rotation of this shaft provides the motion for all of the Baby Furby's outputs. The eyelids are driven off of a single closed cam path, the mouth off of two closed cam paths on the two sides of the center cam, and the leg/body movement is driven by the final cam which is isolated from the rest of the system by an additional breakaway clutch.

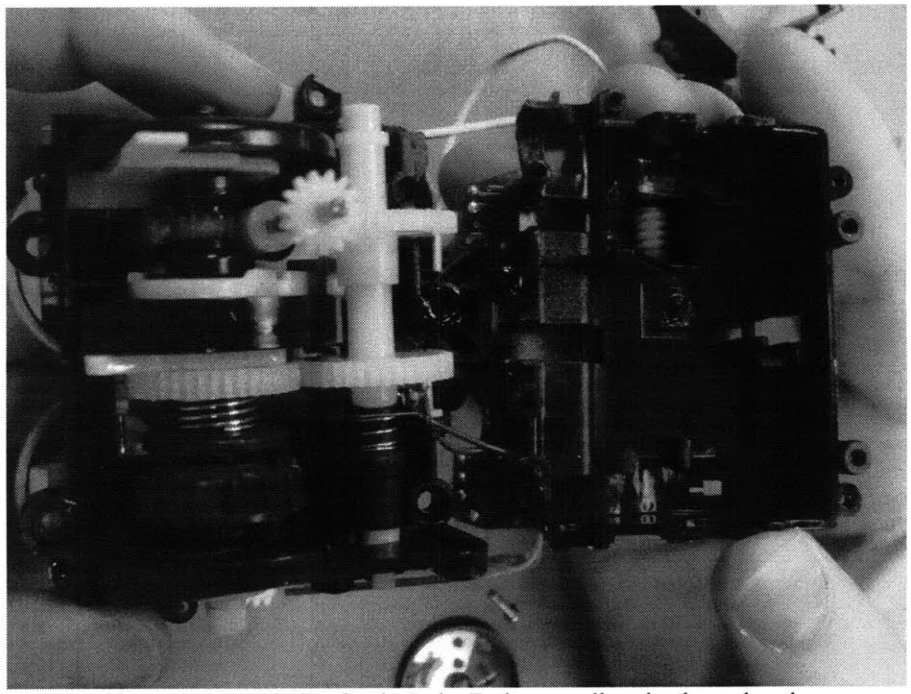

Figure 5: The main transmission for the Baby Furby as well as the three closed cams which drive all of the outputs are visible in this picture. The output from the motor, which is located behind the right piece, passes through two worm gear reductions before driving the main cam shaft. The cam on the top drives the eyelids, the two sides of the middle cam drive the mouth motion, and the lower cam drives the legs. Between the upper cams and the cam for the legs is another clutch mechanism which further protects the drive system from unexpected torques to the legs.

The appearance of independence is generated by running the cam shaft forward and backwards through limited angular ranges where one or several of the action are generated. This allows for relatively realistic representation of simple cyclic behavior such as blinking and chewing, but implementing more complex behavior with this type of system would not be possible without dramatically increasing the scale of the cams.

As was the case with the lower body segment of the Baby Furby, the elements in this region of the toy also very densely packed, and the break away clutch on the leg output indicates the importance of separating the relatively fragile internal components from external torques. This isolation is also present in the final segment of the actuation system between the cams and the facial features. In this case, the isolation is accomplished using semi-compliant plastic connections to the output components that can be seen in figure 6.

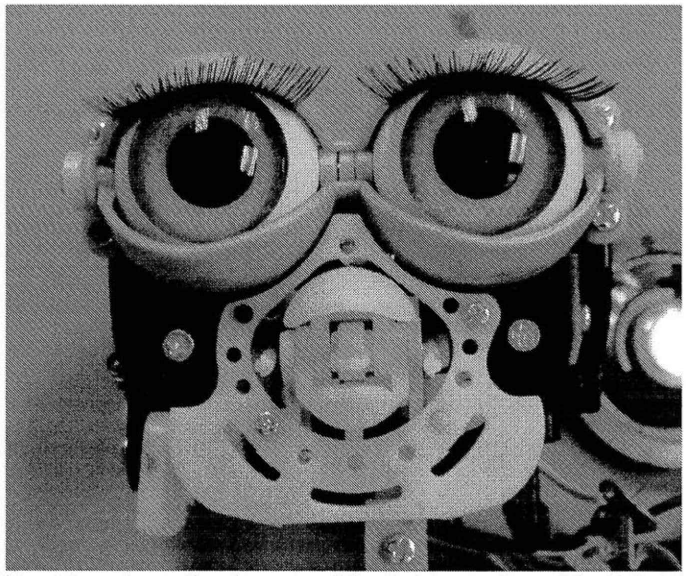

Figure 6: This picture shows the elements of the facial actuation of the Baby Furby. The final semi-compliant components of the transmission are visible as is the small lever inside the mouth which actuates a switch to provide the mouth input. The small circuit board on the right side contains the rotary switches similar to the ones used for the legs which give the rough position of the the cams.

2.1.2 Conclusions from the Baby Furby

The examination of the Baby Furby provided important information about the existing actuation systems used by Hasbro in its toys and also helped to identify key design considerations for any new actuation system. The current actuation system for the baby Furby is both very simple and very complex. The use of only one actuator and very simple sensors makes the system control simple and reduces the cost of the toy, but the large torque increase required, as well as the need to create the appearance of independent outputs has led to a substantial amount of gearing and significant use of cams. The main gear drive trains are a significant source of mechanical noise within the toy that detracts from its realism and believability. In addition, the space requirements of these elements lead to a toy with and extremely dense interior increasing the design challenges for similar toys.

The observations from the disassembly of the Baby Furby also point to several areas for potential improvements. Two of the largest of these areas are the noise created by the actuation systems and the limited output options offered by the cam drive system. The mechanical sounds produced, in large part, by the gear trains detract from the realism of the toy and also indicate the potential for improved efficiency. A higher torque actuator would eliminate the need for the extensive gear train and could help solve these problems. Another solution to this problem would be the design of a transmission that was quieter. On the output side, the system used in the Baby Furby does do a good job of representing simple cyclical motions, but more complex and realistic behavior would require truly independent actuation. If a new more compact and inexpensive actuation system could be developed it would become feasible to include several independent actuators allowing for new degrees of interaction between the toy and user as well as simulation of more complex non-cyclic behavior.

2.2 The FurReal™ Series of Toys

A separate series of Hasbro mechatronic toys called FurReal was also one of the targets of improvement. These toys are designed to simulate a variety of animals and provide in character feedback to the user. The scale of these toys ranges from the size of the Baby Furby, up to a pony called Butterscotch that is large enough to have children sit on it. These toys have outputs similar to those of the Baby Furby, such as movement of the eyes, mouth, limbs, and tail but seek to represent real animals and thus make appropriate sounds instead of speech.

2.2.1 Examination of the Newborn Cub

Following the disassembly of the Baby Furby a Newborn Cub from the FurReal series of toys was disassembled to provide a comparative reference. Prior to disassembly user style testing was done which revealed that, unlike the Baby Furby, it appeared that more than one action was always taking place which detracted somewhat from the realism of the toy. The lack of independence in actions such as blinking led to a very mechanical feel since the toy was either in full action or not, with no passive motion. The believability of the toy was also reduced by mechanical noise similar to that which was present in the Baby Furby. Relative to the Baby Furby, the Newborn Cub is larger but like the Baby Furby it has three main outputs. The outputs on the Newborn Cub are movement of the front two legs, movement of the eyes, and the movement of the tail.

When the outer fur like covering is removed plastic housings and linkages similar to those in the Baby Furby are revealed. One area of difference is in the contact sensors that are placed under the fur. On the Baby Furby the sensor is composed of a series of wires run back and forth across the chest, where as the Newborn Cub has a plastic piece on its back which is attached to a switch. This plastic component can be seen on the top of the back of the Newborn Cub in figure 7.

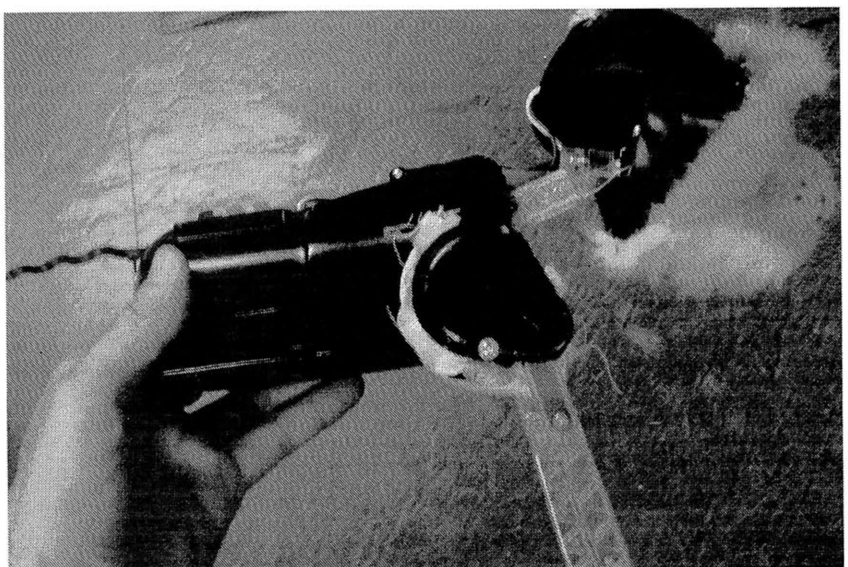

Figure 7: The Newborn Cub with the outer covering removed. The front legs, eyes, and tail are the three mechanical outputs of the toy. The input sensors are both touch based and are located on the back of the toy, and inside the mouth.

Once the plastic housing is removed it is possible to see several similarities with the actuation system of the Baby Furby, with the inclusion of a few additional elements. The plastic spur gears and closed cams which composed the main elements of the Baby Furby's actuation system are also present in the Newborn Cub and appear prominently in figure 8, but there is less focus on using cams to drive the outputs. The movement of the eyes is driven by a closed cam, while the legs are driven by a combination of two spur gears and a sliding linkage.

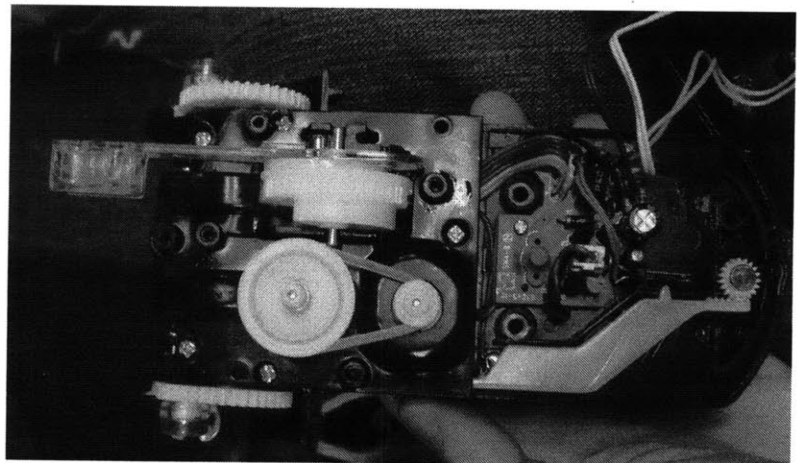

Figure 8: The Newborn Cub with the outer housing removed. The actuation system uses plastic spur gears and cams similar to those in the Baby Furby, but also uses a belt drive system for a portion of the initial torque increase from the motor output.

The tail is driven by a rack on an extended sliding link which is indexed by a Geneva gear which can be seen in the center of figure 9.

The first major difference in the actuation system is in the power transmission. Unlike the Baby Furby which used two worm gear assemblies in series, the Newborn Cub uses a belt drive reduction for the first transmission stage, and a worm gear for the second. Also noticeably absent is any type of clutch system to isolate the internal components of the actuation system from external torques. In addition there are no internal sensors to determine the position of elements of the actuation system. The absence of the this type of sensor and the use of only one double sided cam reduces the appearance of semi-independence and the overall complexity of the outputs which is observable from user-style interaction with the toy.

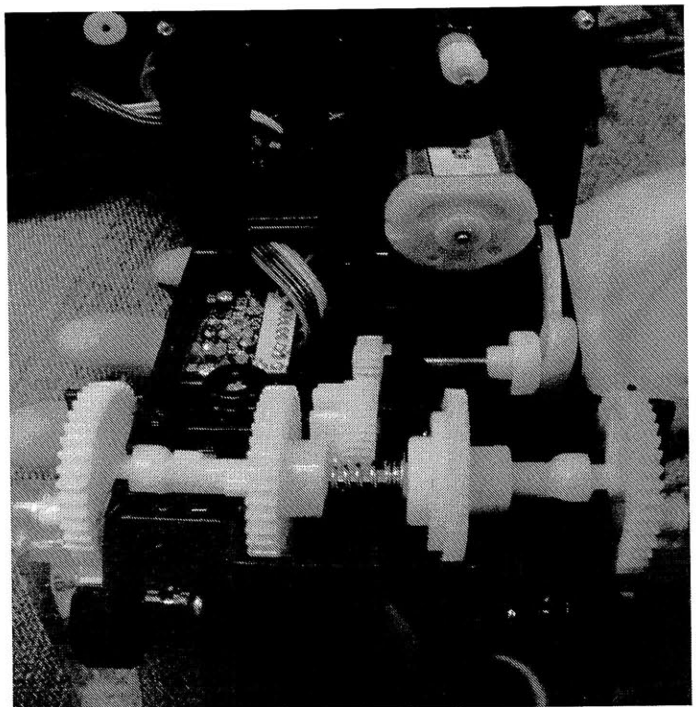

Figure 9: The actuation system of the Newborn Cub with the housing holding the belt drive system raised. The worm gear on the axis parallel to the motor is connected to the larger belt driven pulley visible in figure 8. In the center of the picture is the Geneva gear which indexes the tail through the sliding link on the right side. The front gearing drives the two front legs of the toy as well as the cam which moves the eyes. The spring in the center is not a component of a clutch system, but is used solely to separate the two center gears.

2.2.2 Conclusions from the Newborn Cub

The Newborn Cub is, on the whole, a more simple design than that of the Baby Furby. The larger size of the toy leads to a significantly reduced internal component density and the reduced appearance of independence in the outputs simplifies the actuation system. The use of a belt drive for a portion of the torque increasing transmission indicates that belts could potentially be more widely used which would have the potential to reduce the mechanical noise produced by the toy and thus increase its believability. The lack of any type of clutch within the drive train indicates that there is less of a focus on isolating the integral elements of the actuation system. This design decision could be based on the lack of a need for insuring that all of the elements remain in alignment with each other in order to preserve the appearance of independence in the outputs, the reduced chance of back drive due to the construction of the output components, or may simply be a cost saving measure.

The observations about the actuation system also lead to several design considerations for new actuation systems. The first of these it that there is a potential to use a belt drive system to provide the torque increase the toy requires. The use of belts could significantly reduce the mechanical noise the toy produces, but would most likely require more space to implement. The use of a motor which is visually identical to the one in the Baby Furby suggests that there is a desire to standardize components across toys and that the torque requirements of particular toys are achieved by tailoring the transmission, not the motor. This suggests that a new actuation system would have to be versatile and adaptable to a variety of different toy designs and be able to be easily integrated into a torque adjusting transmission. The lack of a clutch in the Newborn Cub indicates that it is not necessarily standard practice to include this type of protection, and thus an actuation system which was resistant to back drive damage would be favorable.

3.0 Potential New Actuation Systems

The design of a new actuation system began with a very broad set of potential objectives set by Hasbro. These potential objectives included designing an actuation system that was novel, more efficient, cheaper, or allowed more realism. With these broad goals, the lab brainstorming sessions naturally produced a wide variety of potential ideas which each satisfied some subset of the objectives. This large pool of potential ideas was narrowed to a several ideas that were investigated further. The first of these ideas was the use of flexible shafts.

3.1 Flexible Shafts

The large number of power transmission elements on the inside of the toys examined, along with the use of long linkages or racks to transfer power from a central actuator to distant parts of the toys, prompted the idea of using flexible shafts to transfer power. The central idea behind this concept is the use of a flexible rod or tube which has a high torsion stiffness. When this type of material is placed within a flexible tube that has a low coefficient of friction with the shaft it is possible to transmit rotary motion through the shaft even when it is curved, or is being deflected. The potential uses of this type of system in toys could be significant. In many of the toys examined there is only a single drive motor. The power from this motor drives all of the outputs of the toy through a series of gears, linkages, and cams. For outputs that are on a moving component, coupling the output to the main actuator can be difficult. The use of a flexible shaft would eliminate the difficulty of transferring power from the stationary actuator to the output on a moving component. In addition the ability to curve the shaft would allow for more easy routing of power through densely constructed toys.

The initial sketch model for a flexible shaft system, which can be seen in figure 10, used two coaxial plastic tubes. The inner tube, which functioned as the drive shaft, was connected to a motor from one of the smaller disassembled toys. Tests conducted with this sketch model demonstrated that the basic principles of the system worked, but that the radius of the bends in the shaft did affect the output performance. Following this successful test, work is currently underway to replace parts of the actuation system of one of the larger toys with a flexible shaft drive. The results of this test and feedback from Hasbro will give further direction to the future of this project.

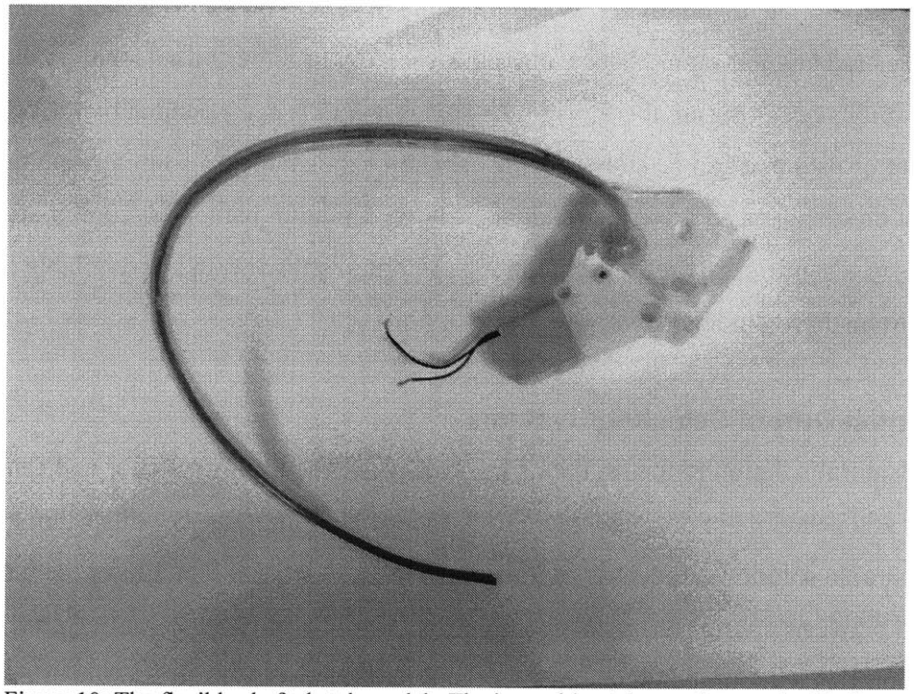

Figure 10: The flexible shaft sketch model. The inner drive tube can be seen inside the translucent outer tube. Rotation of the motor in the plastic housing produces rotation of the inner shaft when the outer shaft is properly constrained.

3.2 Output Selection

The use of cams in the Baby Furby to simulate independent outputs prompted the idea of creating a system that could selectively drive different outputs. This type of system would allow more independent outputs, than actuators in the system, by shifting power from one output path to another. This type of system has several advantages over the cam dwell system used in the Baby Furby. In the cam system the appearance of independence is created by moving the cam shaft through an angular range where only one cam is not in a dwell position. This thus creates only one changing output, and the appearance of independent motion.

The problem with this system is that it requires that the outputs be cyclic, in a predefined mechanical sequence, and can only produce relatively simple motions. These problems are all associated with the use of cams. The need to stay within the dwell period of the other outputs requires that any singular output be relatively short, or be able to be generated by cycling back and forward through the dwell range. When it is time to switch outputs the cams must be rotated to the next desired angular range that requires that the outputs either be adjacent on the cam, or that other motions occur during the transition. This problem is compounded by the relatively small amount of data that can be stored on the cam since the diameter is limited and the radial change must be sufficient to drive the remainder of the actuation path. The combination of these factors leads to a significantly more limited range of outputs than would be available if the outputs could be driven independently.

3.2.1 Potential Output Selecting Systems

The natural solution to the problems created by the use of one actuator and cam systems would be to add actuators in order to create truly independent outputs, but this is not necessarily the most desirable solution, especially in lower cost toys. A system that allows the motor power to be shifted between a series of independent outputs would allow for a significant increase in the output possibilities without the increased space and cost requirements of additional motors and the transmission stages associated with each of them. The use of a switching transmission would allow for the independent actuation of one or more outputs by creating separate output paths for each desired combination and then transferring the power of the motor to the path which has the desired outputs. A diagram demonstrating this concept is shown in figure 11.

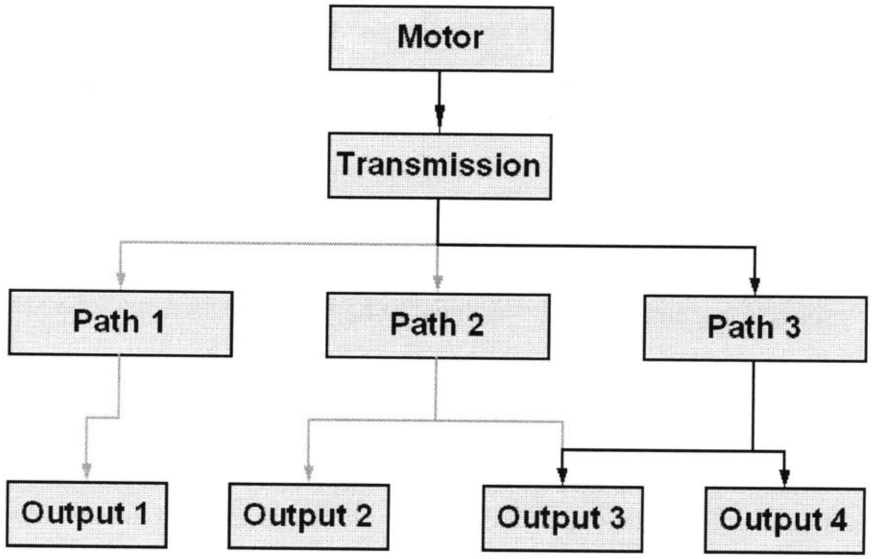

Figure 11: This diagram shows the path of power from the motor to the outputs utilizing an output selecting transmission. The system depicted uses only one motor and torque increasing transmission, but delivers three different independent output options denoted as paths 1, 2, and 3. Each of these output paths activates a different set of one or more of the outputs allowing for more complex actuation of the outputs. In this case path 3 is selected which produces the actuation of outputs 3 and 4. The main disadvantages of the system are that only one path may be utilized at a time, and depending on the implementation, the output for each path may be only one directional.

The main problem with this type of system is actuating the switching transmission. There are several possible ways to accomplish the actuation, but all have drawbacks. The first option is to use rotation of the motor in one direction to drive the system and use rotation in the other direction to switch between outputs. This method has the advantages of being relatively simple, and requiring only one actuator, but also has the major disadvantage of only being able to drive the outputs in one direction, which would thus require the outputs to be cyclical.

Another possible method for actuating the switching transmission is to have the shifting be based on the angular velocity of the transmission input. This type of transmission would allow for the outputs to be driven in both directions using only one actuator. The differences in speed between the outputs could either be used directly, or compensated for with an additional transmission stage. The major disadvantage of this system is that the motor requires time to accelerate between various velocity ranges and thus there is a predefined order to the actuation of components, and there may be undesirable actuation of outputs as the shift to the desired output angular velocity is made. In addition the potential need to add additional transmission stages to compensate for the differing angular velocities would add cost to the toy and increase the mechanical noise produced.

A third option is to include a second actuator that provides the actuation for the switching transmission. The use of a second actuator allows for both the transmission and the main drive to be run in both directions, eliminates the problem of having undesired motion as shifting occurs, and allows the widest range of output options, but requires the addition of another actuator and the additional cost and space associated with it. This cost could be reduced by using a smaller motor than is used in the main drive, or possibly using a voice coil drive, but even these solutions will most likely increase the final cost and complexity of the toy. As table 1 shows each of the switching systems offers advantages over the cam drive system, but no one option provides all of the potential benefits.

	Cam Drive	Direction Driven Switching	Velocity Driven Switching	Multi-actuator Switching
Uses only one actuator	X	X	X	
Allows actuation in both directions	X		X	X
Allows switching without additional output movement		X		X
Allows for more control options than cam drive		X	X	X

Table 1: This table shows the advantages and disadvantages of three types of switching transmissions as well as the cam transmission currently implemented. Each switching transmission provides more control options than the current cam drive systems, but each one has only 2 out of the 3 other beneficial characteristics.

The two systems that seem to offer the more promising options are the direction driven switching and the multi-actuator switching. These two options have the advantage of allowing shifting between outputs without unintended motion which would detract from the realism, and also are simpler since a velocity based clutch is not required. The implementation of these systems could take a variety of forms, but two means considered for implementation were a system using a one piece cam shaft, or a system using a single larger internal cam. The cam shaft system uses one cam shaft to move a series of idlers in and out of contact with input and output gears or rollers. An example of a potential version of this system is shown in figure 12. This system has the advantage of being able to drive a large number of outputs and having relatively few, and simple components. The disadvantages are that the system could be quite large and have a low efficiency.

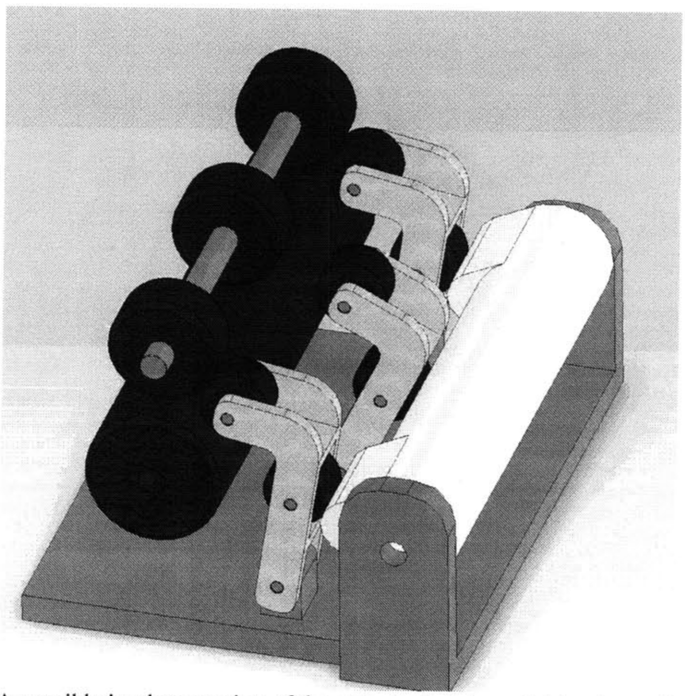

Figure 12: A possible implementation of the cam shaft style switching transmission. The desired output is selected by rotating the cam shaft on the right which moves the idler rollers into and out of contact with the lower drive roller and the upper output rollers.

The other method that was considered uses a large internal cam to move the output components into and out of contact with a central drive wheel. This type of system is illustrated in figure 13. Different output groupings are programmed by arranging the high and low points on the cam so that all of the outputs which are desired have a high point at the same angular position. One of the complications with this style of system is that it requires that the output rollers be able to move short distances in the radial directions which could be challenging to implement. This problem might be best overcome by having the output rollers attached to flexible shafts that could accommodate the movement. The main disadvantages of this system are the large disk shaped profile of the transmission, the difficulty of having the output rollers move in and out radially, and the speed increasing effect of having the large central drive wheel turning the small output rollers.

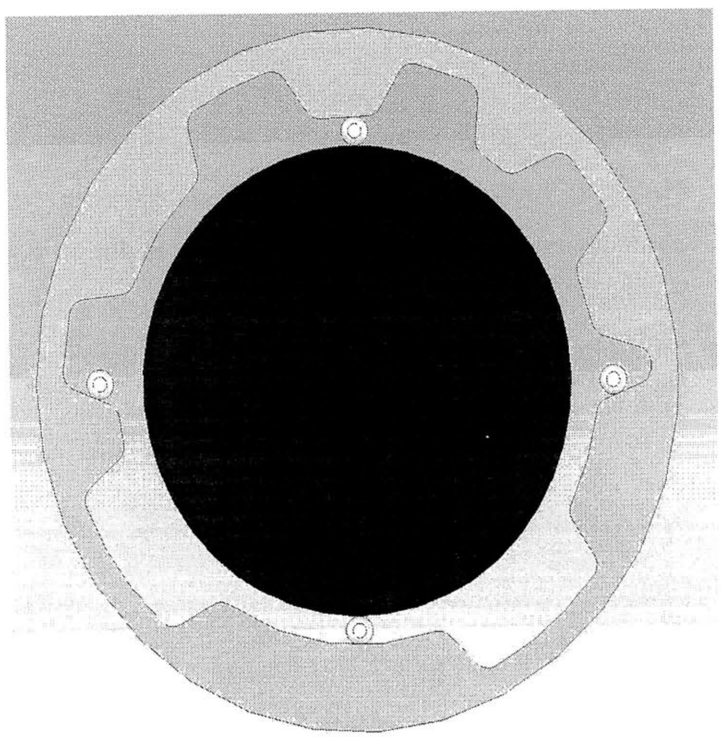

Figure 13: A possible implementation of an output selection system using a large internal cam. This system has a central drive wheel and 4 small followers which are linked to the system outputs. The desired outputs are selected by rotating the cam.

3.2.2 Output Selection Summary

An output selection system has the potential to provide a larger number of independent outputs from an actuation without a similar increase in the number of actuators. The ability to select different outputs, or groups of outputs to drive, as well as the actual independence of the outputs increases options for the number and type of outputs and thus provides the opportunity for increased realism in mechatronic toys. Each of the potential output selection systems provides some advantages over the currently used cam drive system, but none of these systems provide all of the desired actuation features. The two systems that hold the most promise are the directional switching, and multi-actuator systems due to their lower complexity and the lack of undesired motion during shifting. Two different potential systems using cams to switch outputs were briefly examined, but no further research into this area was conducted.

3.3 Voice Coil Actuation

One of the more novel potential concepts developed was to use small-scale voice coils to produce the actuation for these types of toys. The use of voice coils was first considered due to the roughly linear nature of the motion produced by the cam systems inside of the Baby Furby. If voice coils could be used directly it would eliminate the need to use the cam system and could dramatically reduce the complexity of the toy while providing truly independent actuation of all of the outputs. The main problems with implementing direct voice coil drive is the force and stroke requirements of the systems outputs. In the toys examined the majority of the outputs required a motion between .25 and .5 inches. This movement is significantly larger than the stroke output of low cost and low power voice coil systems. This problem could potentially be overcome by using a displacement multiplying transmission or flexure, but this adds to the complexity of the system and reduces the output force. The low output force could be acceptable for the facial motions of some of the toys, but would not be sufficient to drive the body motions.

3.3.1 Integrating Voice Coils into Existing Actuation Systems

The problems inherent in the direct use of voice coils led to the idea of integrating these actuators into the transmission and drive system within existing toy designs. The largest problem in implementing this type of system is that the linear output of the voice coil must be converted into a rotational motion. This problem is not new, it is the same as the one encountered in virtually any kind of combustion engine, but there are several significant problems which prevent conversion methods similar to those used in an engine with cylinders.

The first of these problems is that it is desirable to use only one voice coil. As is the case in single cylinder engines, dynamically balancing the use of one linear actuator to drive a crank shaft is not a simple task. In addition, such a system would most likely require a starter mechanism to prevent the motor from becoming stuck in a singularity position. These two problems alone create major obstacles to producing cheap and realistic actuation. With the idea of using a crank shaft effectively eliminated, other existing mechanical conversion methods were examined.

3.3.2 Screw Drive Voice Coil Transmissions

The next promising option for converting linear motion into rotary motion involved the use of a helical surface, like those used in a screw or bolt. Both screws and bolts transform rotational motion into linear motion, but are generally not backdrivable. In order to use this method, the helical surface would either have to have a very low pitch, or an extremely low coefficient of friction with the matching piece. Currently, systems such as ball screw assemblies provide and example of how such a mechanism would work. Counter to the way they are typically used, many lower pitch and low friction ball screws can be backdriven by moving the nut. This linear motion causes the screw to rotate, and could provide the conversion which is required.

In order for this type of screw drive system to be feasible in a toy design application the screw would have to be low cost and very small. These requirements effectively eliminate ball screw designs since the rolling element bearing assemblies required are generally more costly than many complete toys. The elimination of ball screws leaves the possibility of using a lead screw type design. The higher friction in this type of design requires that the pitch of the screw be much larger in order to allow for backdriveablity. The high required pitch coupled with the millimeter scale motion provided by small voice coils would produce extremely small rotations per stroke of the voice coil. The high frequency capability of a voice coil could be used to help compensate for this, but there remains a problem. In order to generate large rotation in one direction, it is necessary to add one or more one way clutches into the system. The extremely limited rotation of a screw drive system creates problems in this area because of the backlash that may be present in the clutch mechanism. In order for rotation to be produced, and to avoid high inefficiencies, the rotation must be significantly larger than the backlash in the clutch. This problem might be addressed by using a flexural clutch such as the one shown in figure 14. This type of clutch mechanism provides only a very limited maximum torque transmission, but also has virtually no lash.

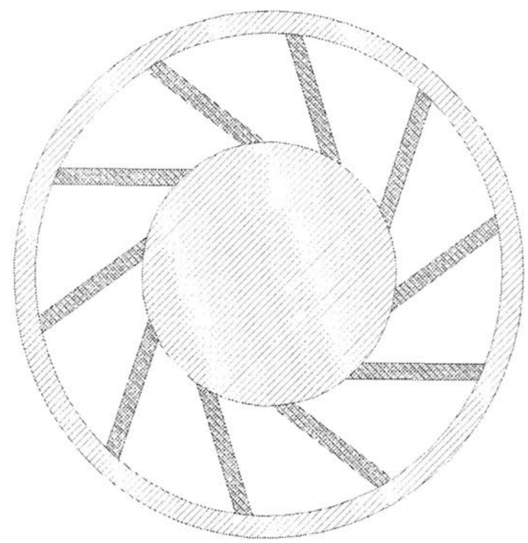

Figure 14: An example of a one way flexural clutch mechanism. When the central rod is rotated clockwise the arms slide along either the rod or the outer ring. When the central rod is turned counterclockwise the flexures lock against the surface in a manner similar to self energizing brakes and couple the rod and ring.

The use of this type of clutch might make the use of a screw drive possible, however the cost of the components would still be a major issue. The side benefit of examining flexural clutches was that it led to the idea of using a flexure to convert the linear motion of the voice coil into rotational motion.

3.3.3 Flexure Based Voice Coil Transmissions

The short output stroke of the small-scale voice coils is a major problem when using a screw type mechanism, but this small stroke is actually advantageous when the use of flexures is considered. While a screw drive requires large motions, the use of flexures is limited to small movements which fall within the elastic deformation range of the material. A flexure system that would convert small, high frequency motions of a voice coil into pulses of rotation could take the place of a much more expensive screw drive system.

The first attempt to create a sketch model of a flexure system which would allow for the conversion of pulses of linear motion into rotational motion produced a simple, but functional conversion system which is shown in figure 15. This system used two foam disks with wooden beams placed into one of the disks at an upward angle. As the distance between the two disks is reduced the compression of the beams forces the disks to rotate relative to each other. If one of the disks is placed on a shaft and the other disk is pressed into it repeatedly one directional rotation is generated.

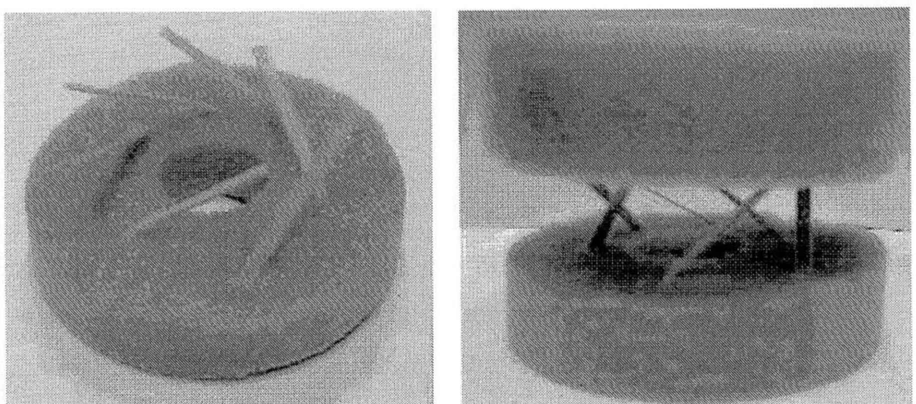

Figure 15: The first sketch model of a flexural transmission system to convert pulses of linear motion into rotational motion. When the two disks are pushed together the beams in the center force them to rotate relative to each other.

The underlying phenomenon that drives the rotation is essentially the same as a two-dimensional, parallel-four-bar linkage that is shown in figure 16. When the upper beam is pushed downward from this position it also moves to the right because of the geometric constraints. If this type of structure is applied around the circumference of a circle the geometry in the sketch model is created. This geometry forces the two disks to rotate relative to each other as the distance between the surfaces changes. The only problem is that, as in the linkage, when the upper beam is lifted the movement is reversed. This problem is solved in the sketch model by placing one of the disks on a shaft with a loose friction fit that acts as a one-way clutch. As the disks are compressed the force of the compression overcomes the friction and drives the disk to rotate, but when the compression is removed the friction prevents the counter rotation. The combination of this system of flexures and a one-way clutch allows for the production of one directional rotational motion from each compression-cycle of the disk and flexure assembly.

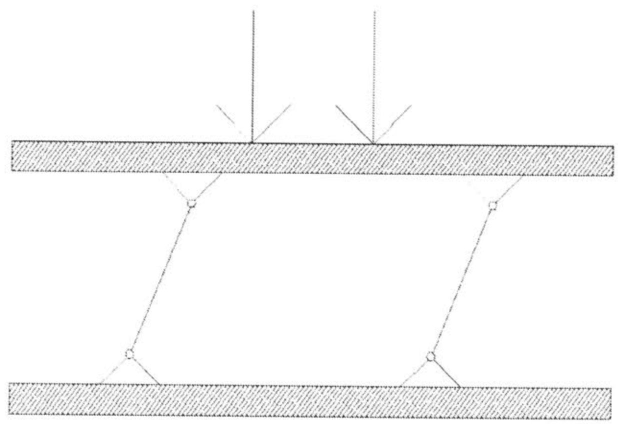

Figure 16: The basic principle of the flexural transmission is the same as the linkage system shown here. When the top plate is pressed down the parallel four bar linkage forces it to also move to the right. If this two dimensional model is applied around the circumference of a circle the flexure geometry is generated.

After confirming the basic mechanical principals using the sketch model, and receiving favorable feedback on the idea from Hasbro, the generation of a more realistic proof of concept model was undertaken. In this model the goal was to reduce the scale to a more realistic size and to use both a flexure and a voice coil that could be similar to a production product. The first part of this design process was determining how to easily produce a flexure system at or near the desired scale.

The first major design question in developing the flexure was whether it would have to approximate a spherical joint. In the linkage assembly shown in figure 16, the joints are purely rotational, but when this structure is applied around the circumference of a circle the geometry becomes more complicated. If one end of the flexure is considered to be effectively a cantilevered beam and the other side considered to be a fixed pivot, due to the contact friction, then as the disks are compressed the cantilevered side must flex in multiple directions. This motion is difficult to represent in two dimensions, but the illustrations in figure 17 give a rough approximation of the two motions.

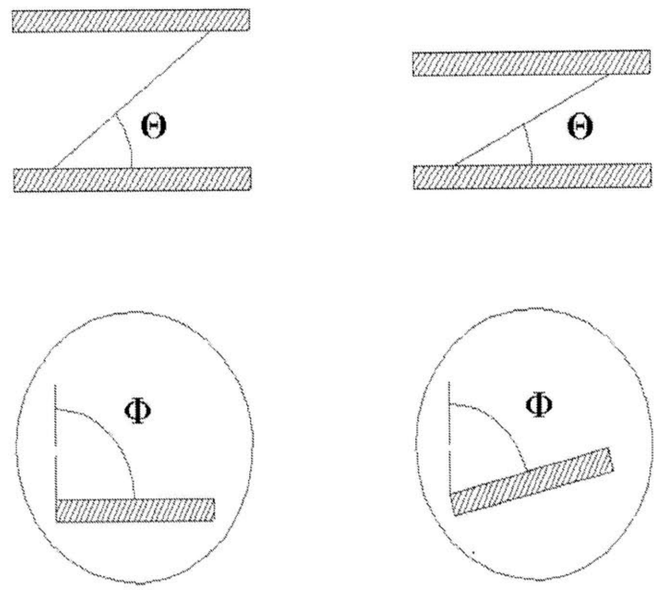

Figure 17: These sketches show the two rotations that the flexure undergoes when the disks are compressed together. The top sketches show the side view of the assembly while the bottom sketches show a top view where the disks are transparent. The sketches on the left are uncompressed and the ones on the right are compressed. As the disks are compressed the angle of the flexure relative to the plane of the disks, Θ, decreases. The compression also makes the length of the flexure in the plane of the disks longer which changes the angle of the flexure within the plane of the disks which is represented by Φ.

If the motions of the flexure requires significant deflection in both directions then it would be significantly more difficult to manufacture than if this motion could be approximated as a one dimensional rotation. Working with the assumption that the frictional constraint and out of plane bending would allow some rotation on the Φ axis, work on a simple to manufacture flexure began.

In order to make the flexure both inexpensive and easy to manufacture a design that could be stamped into sheets of spring steel was decided on. This design would allow for easy manufacturing of the thin flexure material and keep the cost of the flexures very low. The decision was made to create disks that were one inch in diameter in order to approximate the scale of the final components. Two designs were created based using five arms arrayed around the circumference of the disk. These two designs are shown in figure 18.

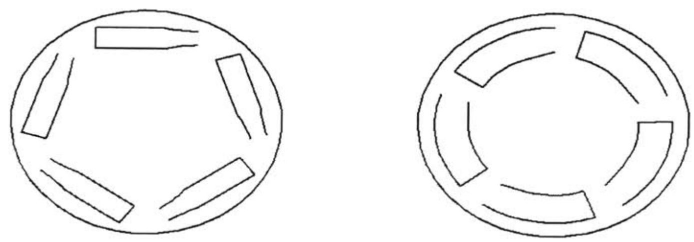

Figure 18: The two profiles for the sheet metal flexures. The metal is cut along all of the lines in the drawing and then the 5 arms on each disk are bent up to form the flexure.

The three parameters central to the design of the flexure are the number of arms, their radial distance from the center of the disk, and their length. The number of arms and the length of the arms both determine the stiffness of the flexure, while the radial distance from the center effects the torque output which is generated. The initial series of prototype flexures were cut from sheets of stainless steel shim stock with thickness ranging from .005 to .015 inches to give a variety of stiffnesses for testing. An example of one of the completed flexures can be seen in figure 19.

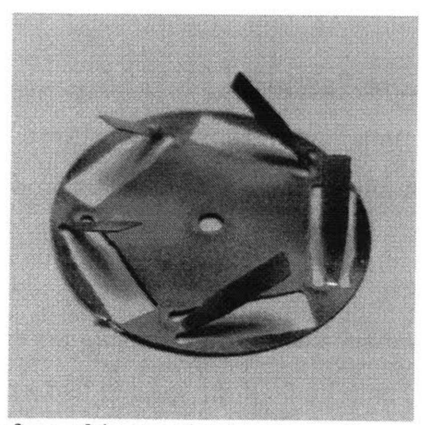

Figure 19: An example of one of the completed prototype flexures.

In order to test the prototype flexures a test setup was constructed consisting of a support for the flexure connected to a .125" inch shaft which was constrained with a one way needle bearing an a bronze sleeve bushing. An exploded view of the test setup is shown in figure 20. The voice coils used in the testing consisted of a range of speakers which had flat plates mounted on their cones. The testing assembly was then placed above the speaker cone so that the flexures were just touching the surface mounted to the speaker cone. The speaker was then driven with a variety of input frequencies and wave forms.

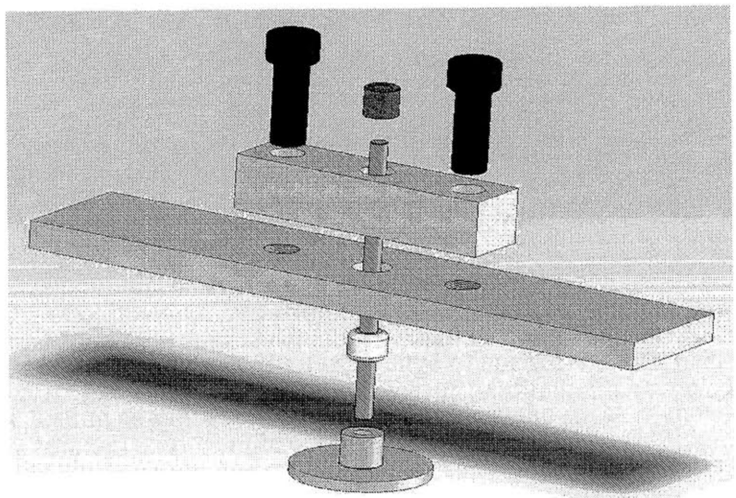

Figure 20: An exploded view of the test setup for the prototype flexures. The one way needle bearing is on the lower part of the shaft and the flexure mounts to the bottom of the disk in the lower portion of the image.

3.3.4 Results of Initial Flexure Testing

The initial testing of the prototype flexures demonstrated that more complicated flexure joints were unnecessary. The simple stainless steel flexures produced rotary motion when driven by the speaker assemblies. In this initial round of testing the torque and speed were measured qualitatively by watching the rotation of the flexure support and by gripping the output shaft. The best torque and speed performance was achieved using the thinnest flexures with the straight arms. The output frequency and amplitude of the speaker had a significant effect on rotational speed with the speed increasing as the frequency increased so long as the amplitude of the cone's motion remained significant. The drop off in amplitude at both lower and higher frequencies led to a rapid decrease in the effectiveness of the flexure transmission. At the maximum output the rotation of disk appeared to be continuous and a torque was produced which was sufficient to make stopping the rotation of the .125 inch shaft by hand difficult.

4.0 Conclusions

This project has made significant progress towards the production of a new actuation system for mechatronic toys, but there remains a great deal of work to be completed. Several ideas including the use of flexible shafts, output switching, and voice coil actuators with flexure transmissions have the potential to solve problems with current actuation designs. Initial proof of concept models for both flexible shafts and voice coil actuators have indicated that these concepts work, but there is still significant work to be done before any commercial product could be created.

In the case of the flexible shaft project there is a need to test additional materials for both of the components of the system as well as a need to try to determine the failure modes of the system and prevent them. In addition quantitative data must be taken about the efficiency of the system in different configurations and with the use of different materials. When these issues are addressed there is also a need to integrate the design into an existing toy system to demonstrate the benefits of using the new technology.

The voice coil actuation system also needs to be tested in an actual toy application, but more development work is necessary before this happens. The current models of the system have proven that the concept can work, but the details of how the friction and compliance of the contact surface effect the performance of the system, as well as the specific requirements for the voice coil need to be developed. The noise, speed, and torque produced by the actuator also need to be quantitatively determined and verified. The measurements for the speed and noise can be made relatively easily with and optical tachometer and a microphone. The measurement of the torque will likely be somewhat more difficult, but could be measured with a low mass de prony brake system. When the effects of these parameters have been quantitatively analyzed and tested, an optimized model can be created to implement in an existing toy.

The work that has been completed on this project demonstrates the potential impact of these new actuation systems on mechatronic toys. In each case these systems have the potential to improve the realism and believability of new and existing devices. The creation of truly independent outputs, and the reduction of mechanical noise will allow for the creation of a product that is both more commercially viable, and also more entertaining for children. There is still a significant amount of work to be done before any of these systems can be deployed, but the potential benefits justify this further research.

5.0 References

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